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## ALIGNMENT EFFECTS IN CORRELATION SPECTRA

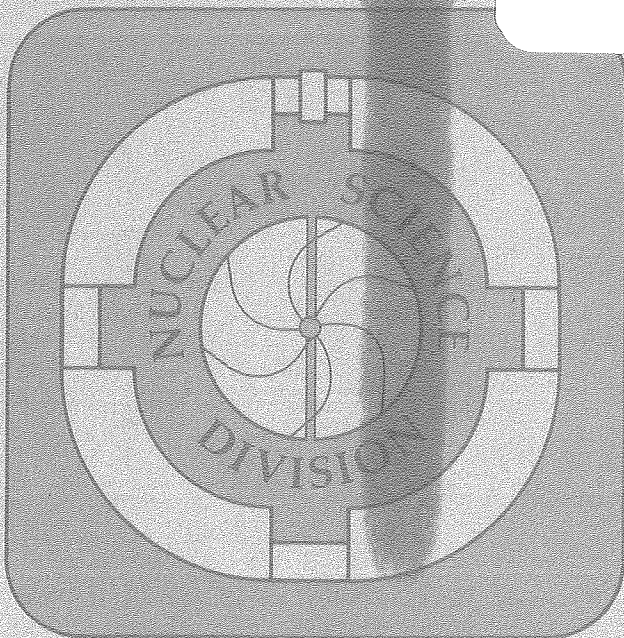
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Alignment Effects in Correlation Spectra\*

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Abstract

The structure of nuclei at very high spins can be studied by measuring correlations between  $\gamma$ -ray energies in the unresolved spectrum emitted. Collective rotations have been shown to produce characteristic features in such correlation spectra. We show here the features produced by the noncollective alignment effects in some high-spin Er nuclei.

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One of the characteristic and fascinating aspects of nuclear structure is the interplay of macroscopic, usually collective, features with microscopic ones that are due to a single (or few) nucleon(s). Nowhere is this better exhibited than in the behavior of nuclei of high angular momentum. Deformed rare-earth nuclei, for example, begin to rotate collectively at low spins ( $\sim 10 \hbar$ ), but this smooth behavior is occasionally interrupted by nuclear "quakes", where the internal structure is changed. The most common change is the decoupling of a pair of nucleons from the deformation and the alignment of their angular momentum with that of the rotating core. This behavior is called "backbending" and has been extensively studied<sup>1,2</sup> up to spins  $\sim 30 \hbar$ , where roughly half the angular momentum is carried in each mode. Above this limit ( $\sim 70 \hbar$  can be accommodated prior to fission and brought in by heavy-ion fusion reactions) the  $\gamma$ -ray spectrum is unresolved and no detailed information exists. The present paper describes a new technique for extracting information on the single-particle behavior from such unresolved spectra.

Many measurements have shown that the unresolved  $\gamma$ -ray spectrum consists of statistical  $\gamma$  rays, which cool the nucleus towards the yrast line and give rise to an exponentially decreasing high-energy tail, and of a lower energy bump, which is composed of yrast-like transitions that remove spin and contain most of the nuclear structure information. Recent  $\gamma$ - $\gamma$  coincidence experiments have shown that it is possible to observe structure in this continuum region;<sup>3,4</sup> the structure is brought out by measuring correlations between the  $\gamma$ -ray energies. Collective rotation of the nucleus is indicated in the two-dimensional  $E_\gamma(1)$ - $E_\gamma(2)$  plots by a valley along the diagonal indicating an absence of two transitions of the same energy--a property of rotational bands--and by the ridges that flank it whose spacing is related

to the band moment of inertia<sup>3,4</sup>. The alignment effects mentioned above give rise to band crossings that seem generally to occur in many bands at a few specific frequencies that are characteristic of the alignment of a few high-j orbitals. In the present note we analyze the effects of such band crossings (backbends) in a correlation spectrum, show that these effects do occur, and give a tentative identification of the high-j orbitals responsible in <sup>158</sup>Er.

A backbend is accompanied by several  $\gamma$  rays of roughly the same energy. An upbend is the clearest example of such behavior and seems to be common at high spins as illustrated by the known second backbends<sup>1,2</sup>. It has been shown<sup>4</sup> that these features appear as bridges across the valley or peaks in the valley of the correlation spectra. All the  $\gamma$ -ray transitions in coincidence with such bridge or peak transitions should be enhanced. If there is more than one backbend in a cascade, there will be a further enhancement of the intensity at the intersection of the two backbend energies. Thus one might expect to see a "square" pattern in the correlation spectra, i.e., intersecting horizontal and vertical stripes with higher than average intensity.

To illustrate this feature, Fig. 1 shows a calculated  $\gamma$ - $\gamma$  correlation plot based on nine cascades with slightly different moments of inertia and using realistic response functions for the detector. Three of these cascades contain one or more upbends at four specific energies (frequencies). These upbends appear as peaks in the valley of Fig. 1 at energies: 800, 1150, 1300, and 1500 keV. The relative population strengths of the upbends are 50%, 24%, 8%, and 10%, respectively. Intense points appear at the intersections of the above rows and columns and they are connected by horizontal and vertical stripes of higher than average intensity.

In the experiment,  $^{156,157,158}\text{Er}$  nuclei were populated at high spin with  $^{122}\text{Sn}(^{40}\text{Ar},\text{xn})$  reactions at 185 MeV. The  $\gamma$  rays were detected in five Ge(Li) detectors placed at 150, 130, and 90 degrees. A sum spectrometer consisting of two 8" x 13" NaI detectors was placed above and below the target as close to each other as the Ge(Li) detectors would allow. Three 5" x 6" NaI detectors filled as much of the gap as possible, completing the sum spectrometer. The energy efficiency of the sum spectrometer was  $\sim 60\%$ . The two large crystals are divided into four sectors each. These eight sectors plus the three 5" x 6" detectors formed a multiplicity filter. Six of the eleven detectors were required to fire in the experiment. The energy deposited in each of the five Ge(Li) detectors together with the total sum energy were recorded event by event. The gains on the five Ge(Li) detectors were carefully matched so the ten different pairs could be combined into one two-dimensional coincidence spectrum.

Because the peak-to-total ratio for the Ge(Li) detectors used was only 10 to 15%, it is very difficult to see the above correlation patterns in the raw data. Therefore a method for subtracting uncorrelated events (Compton and statistical transitions) was used. The method is an improvement on the one previously described<sup>3,4</sup> where the uncorrelated background was generated from the projections of the actual spectra and therefore contained some correlated, as well as the uncorrelated, events. In the present method the correlations obtained in the first step are subtracted from the original projections and these reduced projections are then used to generate a new uncorrelated background spectrum. This process is iterated until the final result becomes stable ( $\sim 20$ -40 iterations). The remaining correlated events are mainly photopeak-photopeak coincidences, for which the detector efficiency is strongly energy dependent ( $\sim E^{-1}$ ). Consequently the detector



efficiency has been divided out. We have shown that there is no change if this is done before or after the iteration. This procedure has been further tested on known discrete-line spectra and on some cases for which Compton suppression reduced the background an order of magnitude.<sup>5</sup>

The result of this procedure is shown in Fig. 2. The three parts a), b), and c) correspond to a low, medium, and high slice, respectively, in the total energy spectrum of the sum spectrometer. A resolution of 40 keV per channel was chosen to give the best ratio of true correlations to statistical fluctuations and still resolve the structures in the correlations. The a'), b'), and c') spectra were generated by first making the projections  $P_i$  of the symmetrized raw spectra of a), b), and c), and then generating a purely uncorrelated two-dimensional spectrum  $N_{ij}$  according to:

$$N_{ij} = P_i P_j / T$$

where  $T$  is the total number of counts. This spectrum is very similar to the original spectrum. To each point of this spectrum are added statistical variations that are randomly selected in a gaussian distribution centered around  $N_{ij}$  with a width  $\sigma = \sqrt{N_{ij}}$ . The resulting spectrum is then treated exactly like the original spectrum and thus shows the effects of the expected statistical fluctuations. These are seen to be small compared to the real correlations for all three sum-energy slices.

The spectra a), b), and c) come from the population regions of increasing total  $\gamma$ -ray energy and thereby from regions of increasing spin. In the spectra this is recognized from the general intensity patterns: spectrum a) has most intensity in the lower left-hand corner; in spectra b) and c) the regions of high intensity move increasingly into the high energy region.

Spectrum a) comes mainly from the 5n channel and the intense square structure in the lower left-hand corner is readily recognized as the 5n lines below the 800 keV blocked backbend in  $^{157}\text{Er}$ . A weaker feature (stripe) at 1100 keV presumably also belongs to the 5n channel since it has high intensity in the region of strong 5n lines (800 keV). This  $\gamma$ -ray energy must correspond to a spin around  $40 \hbar$  and is well above any resolved lines. There is also visible a line at about 850 keV that is not strongly coincident with the 5n lines. This is very likely the well-known second backbend in  $^{158}\text{Er}$ , the 4n product. It is clearly seen in c), and probably also in b), though here it tends to be overshadowed by a stronger line at slightly higher energy.

Spectrum b) comes mainly from the 4n channel. It shows prominent stripes at 440, 500, and 600 keV, which correspond to energies where two or more  $\gamma$  rays have almost the same energy in the first backbend of  $^{158}\text{Er}$ . It is seen how the present technique allows the feeding  $\gamma$  rays to be traced well into the continuum region. At 1060 keV a very intense line is seen. It is strongly coincident with the 4n lines and thus must belong to that channel. It corresponds to the third backbend in  $^{158}\text{Er}$ , which has just been identified from the discrete lines in a study subsequent to this one.<sup>6</sup> This line is also present, though as a weaker feature, in c).

Spectrum c) is populated at the highest spin,  $\sim 50 \hbar$ , producing a spectrum that is roughly flat below 1300 keV. The low-energy lines from the first backbend in the 4n channel are also present in this spectrum, though they are weaker and not so clearly seen on this low resolution plot. The second backbend and the 1060 keV line are clear, as previously mentioned. The dominant feature, however, is the strong line at 1300 keV. It has strong intersections with the low-energy 4n lines, the second



backbend, and the 1060 keV line and thus definitely belongs to the 4n channel. It is impressive that the population at this spin flows strongly through this 1300 keV backbend; whereas when fed at lower spins [ $\sim 40 \hbar$ , in b)] this is almost completely missed. The sum spectrometer thus provides a powerful method for studying those correlations involved in de-exciting particular spin regions.

It seems clear that the enhanced rows and columns in correlation plots like Fig. 2 very probably signal the alignment of the angular momentum of important high-j orbitals. To lowest order a given particle alignment would be expected to occur at a specific frequency independent of the remaining configuration. There are many effects that might tend to spread this frequency, for example, differences in the pairing correlations in different bands. However, at low spins near the yrast line, there are cases observed where several bands cross at nearly the same frequency,<sup>2</sup> and one might expect even less spreading at high spins where the pairing correlations are severely reduced or absent. This is important, since a pileup of many bands is required to explain the observed stripe intensities. Frauendorf<sup>7</sup> has estimated that the high-j orbits,  $\nu(h_{9/2})$ ,  $\pi(h_{9/2})$ ,  $\pi(i_{13/2})$ , and  $\nu(j_{15/2})$ , will reach the Fermi level at frequencies corresponding to transition energies of 1.0, 1.2, 1.6, and 1.8 MeV, respectively. As already mentioned, the line observed at 1060 keV very likely corresponds to the third backbend in  $^{158}\text{Er}$ . This feature is probably caused by the alignment of an  $h_{9/2}$  neutron pair in accord with the theoretical estimate given above and elsewhere.<sup>8</sup> The strong line in Fig. 2c at 1300 keV corresponds well to the estimate given above for the  $h_{9/2}$  proton and we would tentatively make that identification. More systematic data will be needed to make firm assignments throughout the high-spin regions, but the

observation of specific alignment frequencies in an unresolved spectrum represents a significant step in understanding nuclei at the highest angular momentum.

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## References

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<sup>6</sup>J. Burde, E.L. Dines, S. Shih, R.M. Diamond, J. Draper,  
K.H. Lindenberger, C. Schuck, and F.S. Stephens, to be published.

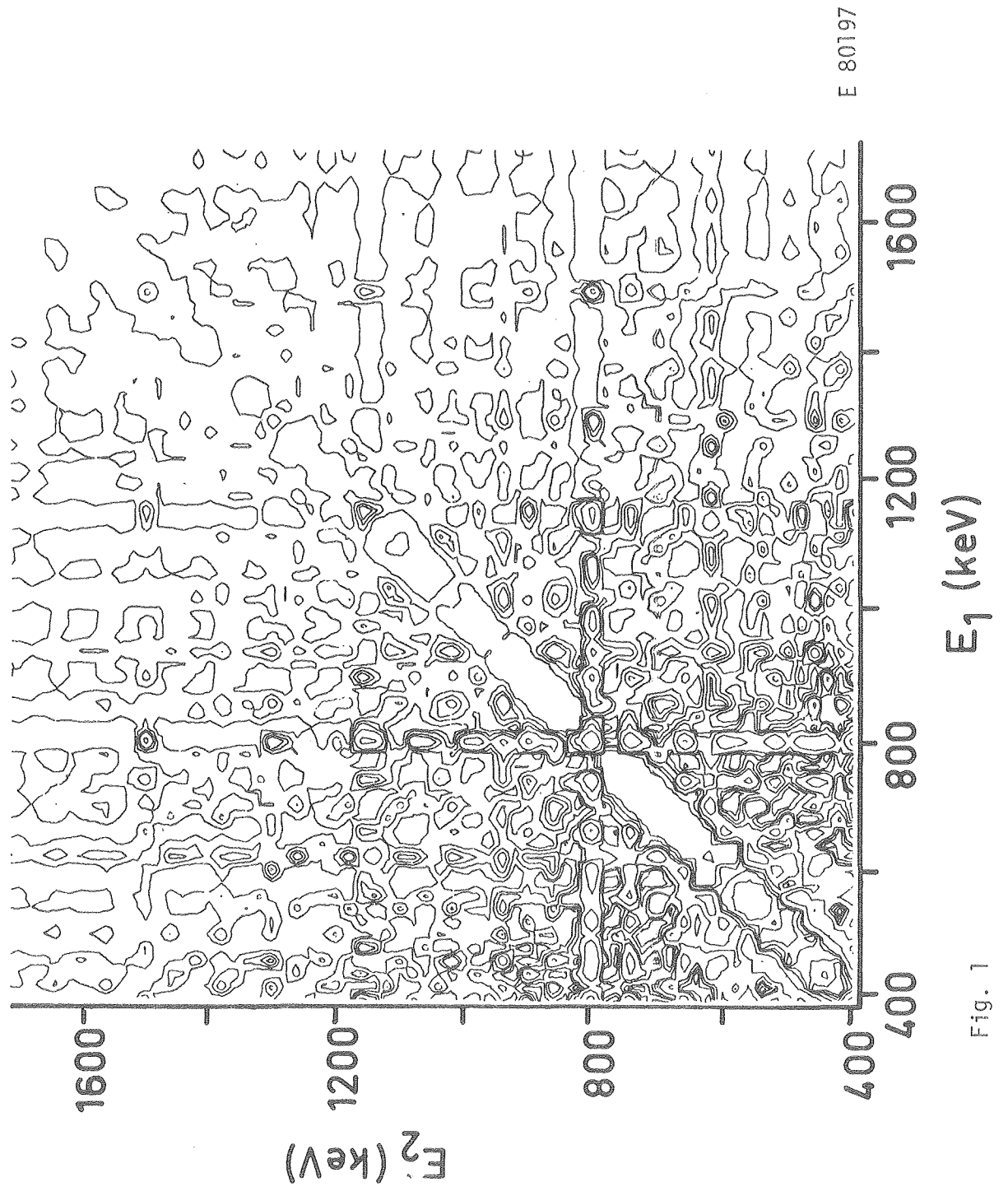
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#### Figure Captions

Fig. 1. Gamma-energy correlation spectrum generated from 9 bands, where 3 go through upbends as described in the text. The raw spectrum contains Compton contributions and uncorrelated (statistical) contributions. The spectrum is treated in the same way as the experimental spectra of Fig. 2.

Fig. 2. Gamma-energy correlation spectra from the  $^{122}\text{Sn}(^{40}\text{Ar}, \text{xn})$  reaction after 20 iterations (see text). Part a), b), and c) correspond to a low, medium, and high energy slice in the sum spectrum. a'), b'), and c') are the corresponding spectra simulating the contributions from statistical fluctuations. After efficiency corrections a standard deviation corresponds to approximately the same number over the entire spectrum. The contour levels are about one standard deviation apart beginning three standard deviations above zero.





# GAMMA ENERGY CORRELATIONS

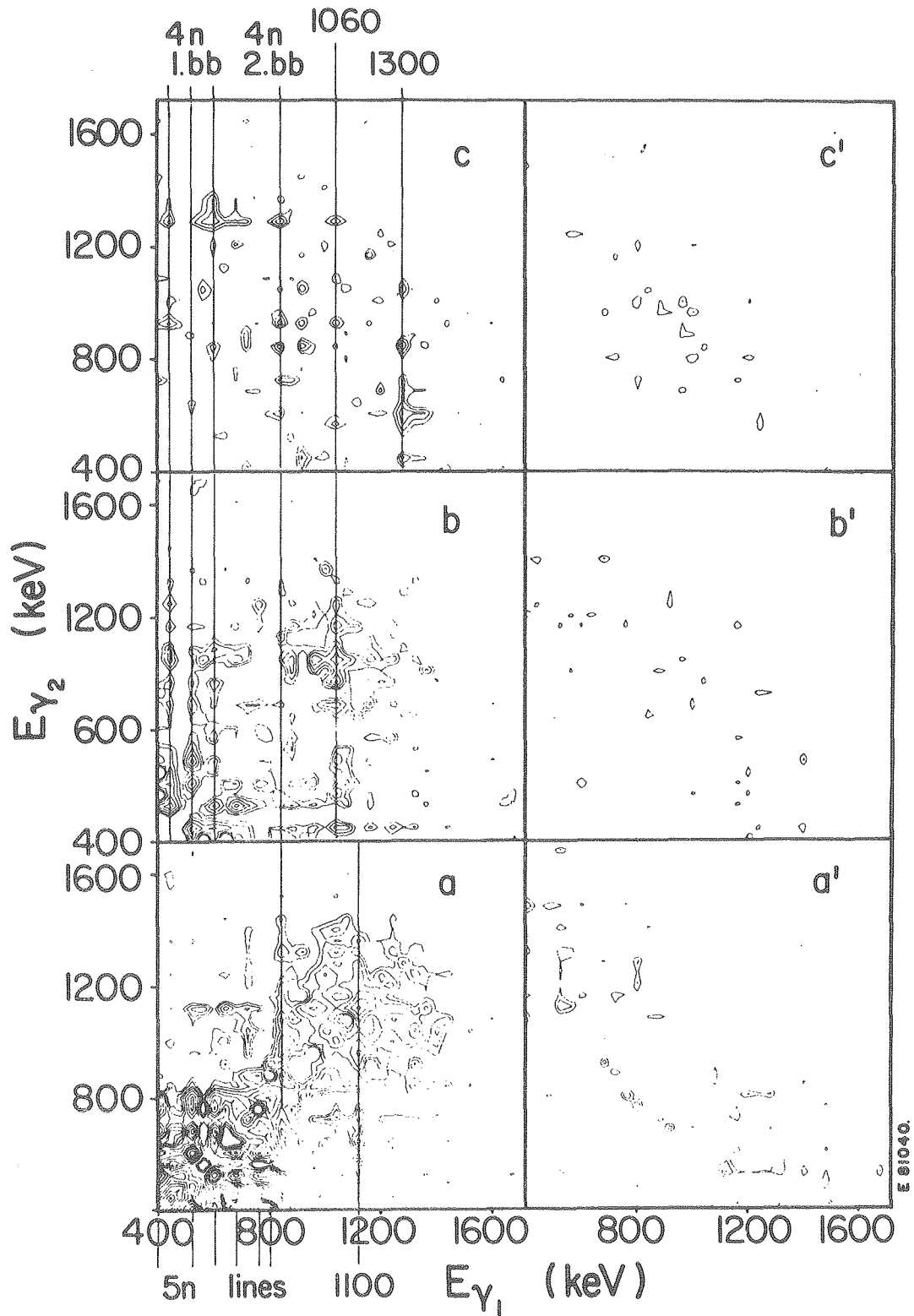


Fig. 2